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Using the X-FEL as a source to investigate photo-pumped X-ray lasers

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Abstract. H-like and He-like resonantly photo-pumped laser schemes were proposed for producing X-ray lasers nearly four decades ago. However, demonstrating these schemes in the laboratory has proven to be elusive. One major challenge has been the difficulty of finding an adequate resonance between a strong pump line and a line in the laser plasma that drives the laser transition. After finding a good resonance, a second challenge has been to simultaneously create the pump and laser plasma in close proximity so as to allow the pump line to transfer its energy to the laser material. With the construction of the X-ray free electron laser (X-FEL) at the SLAC Linac Coherent Light Source (LCLS) researchers now have a tunable X-ray laser source that can be used to replace the pump line in previously proposed laser schemes and allow them to study the physics and feasibility of photo-pumped laser schemes. In this paper we model the Na-pumped Ne X-ray laser scheme that was proposed and studied many years ago by replacing the Na He-α pump line at 1127 eV with the X-FEL at LCLS. We predict large gains greater than 400 cm^{-1} on the 4f – 3d transition at 231 Å.

1 Introduction

Resonantly photo-pumped laser schemes using H-like and He-like ions were proposed for producing X-ray lasers from the earliest days of lasers [1]. Demonstrating these schemes in the laboratory has proven to be very elusive. A major challenge has been the difficulty of finding an adequate resonance between a strong pump line and a line in the laser plasma that drives the laser transition. After finding a good resonance, a second challenge has been to create both the pump and laser plasma in close proximity so as to allow the pump line to transfer its energy to the laser material. With the availability of the X-FEL at LCLS [2] we now have a tunable X-ray laser source that can be used to replace the pump line in previously proposed laser schemes and allow researchers to study the physics and feasibility of photo-pumped laser schemes. In this paper we model the Na-pumped Ne X-ray laser scheme that was proposed and studied many years ago by replacing the Na He-α pump line at 1127 eV with the X-FEL at LCLS. We predict gain on the 4f – 3d transition at 231 Å that is orders of magnitude larger than the gains predicted [3] two decades ago using the Saturn pulsed power machine at Sandia

Table 1. Resonantly photo-pumped laser schemes with 4f – 3d lasing in H and He-like ions							
Pump Line		λ_P (Å)	Absorbing Line		λ_A (Å)	$\Delta\lambda_P/\lambda_P$ (%)	λ_L (Å)
Na	He-α_S	11.003	Ne	He-γ_S	11.000	0.022	231
K	Ly-α_2	3.3521	Cl	Ly-γ_2	3.3511	0.029	64.8
Cr	He-α_T	2.1925	Sc	Ly-γ_2	2.1917	0.036	42.5
Mn	Ly-α_1	1.9247	V	He-γ_S	1.9255	0.040	38.7
Cu	Ly-α_1	1.4253	Fe	Ly-γ_2	1.4253	0.006	27.7
Sr	Ly-α_2	0.82708	Se	Ly-γ_1	0.82765	0.069	16.2
Nb	He-α_S	0.72175	Rb	He-γ_T	0.72143	0.044	14.4

National Laboratory to create the Na pump line. Table 1 shows all the resonantly photo-pumped H and He-like schemes that could lase on the 4f – 3d line that were identified many years ago but which have not yet been demonstrated. The X-FEL can now replace any of these pump lines and enable us to study these lasing schemes.

2 The characteristics of the X-FEL beam at LCLS

With the advent of the X-FEL at the LCLS facility we looked at the characteristics [4] of this laser to see if it would be relevant for exploring photo-pumping X-ray laser schemes. The basic feature of the X-FEL is that it can produce a tunable X-ray source that extends from 800 to 8500 eV. It operates at a 120 Hz repetition rate with approximate output of 10^{12} photons per pulse. The beam has a spectral bandwidth of 0.1% of the fundamental, a pulse duration of 100 - 200 fs, and an unfocused spot size of 400 µm square.
The beam can be focused down to a 1 µm square using X-ray optics. The beam can be rapidly tuned over 3% of the fundamental energy by adjusting the electron beam energy. In earlier calculations [5] we predicted that the photo-ionization rate of Ne gas is about 10 per µsec for the unfocused beam, which is much too slow for using the X-FEL is photo-ionize Ne gas down to the He-like iso-electronic sequence. In this paper we look at the case of a focused X-FEL beam with a 1 µm spot size and 100 fs pulse duration. Using these numbers gives a spectral intensity $I_\varepsilon = 1.6 \times 10^{17}$ W / (eV cm^2). The line strength of the X-FEL beam in photons per mode $n_\varepsilon = 1.579 \times 10^{-5} I_\varepsilon / \varepsilon^3$ where ε is the photon energy in eV. Looking at some typical photon energies $n_\varepsilon = 1765$ at 1127 eV and drops to 9.45 at 6442 eV for the focused beam. For a photo-pumped laser scheme the beam strength in photons per mode is the ratio of the stimulated rate to the spontaneous rate. This is approximately the same

as the maximum fractional population divided by the statistical weight of the level being pumped when the beam strength is much less than one. When the beam strength exceeds one it mean the stimulated rate is much larger than the spontaneous rate and the two levels will be locked into equilibrium with similar populations per statistical weight.

3 Description of the He-like Ne X-ray laser scheme

One of the resonantly photo-pumped schemes that were tried experimentally many years ago was the Na-pumped Ne scheme that used the He-α line of Na to photo-pump the He-γ line of Ne and create gain on several n = 4 to n = 3 transitions in He-like Ne. Figure 1 shows the three principal laser lines that were predicted to have gain, the 4f – 3d line at 231.1 Å, the 4d – 3p line at 231.6 Å, and the 4p – 3s line at 222.7 Å. The 4p – 3s line lases directly from the 4p level that is being photo-pumped. However, it is important to understand that the other two laser lines depend on collisional excitation to transfer population from the 4p to 4d to 4f states. Since these states are very close in energy they tend to equilibrate very quickly if the density of the plasma is high enough.

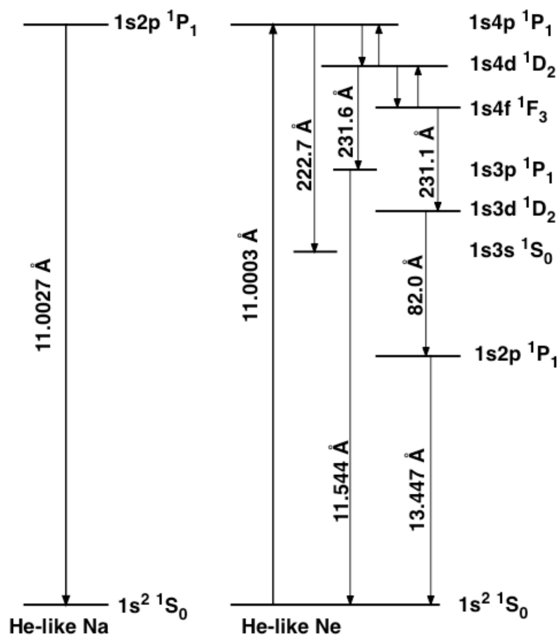

Fig. 1. Energy level diagram for the Na-pumped Ne X-ray laser.

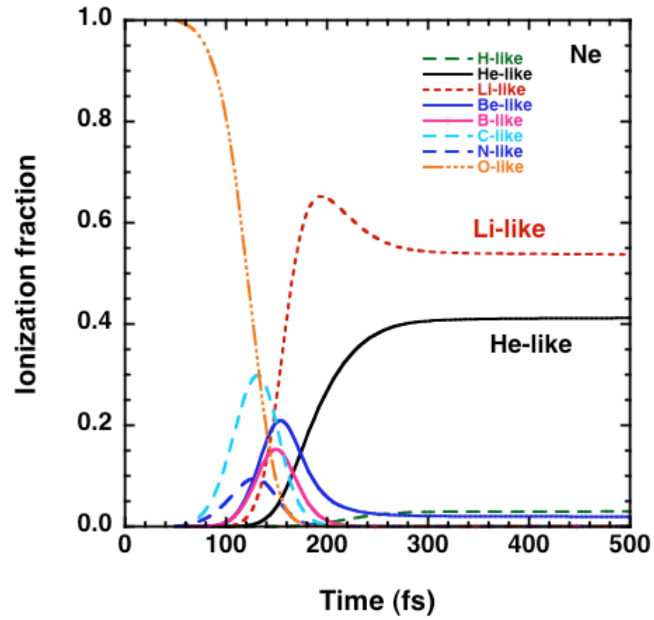

Fig. 2. Fractional population of Ne iso-electronic sequences versus time.

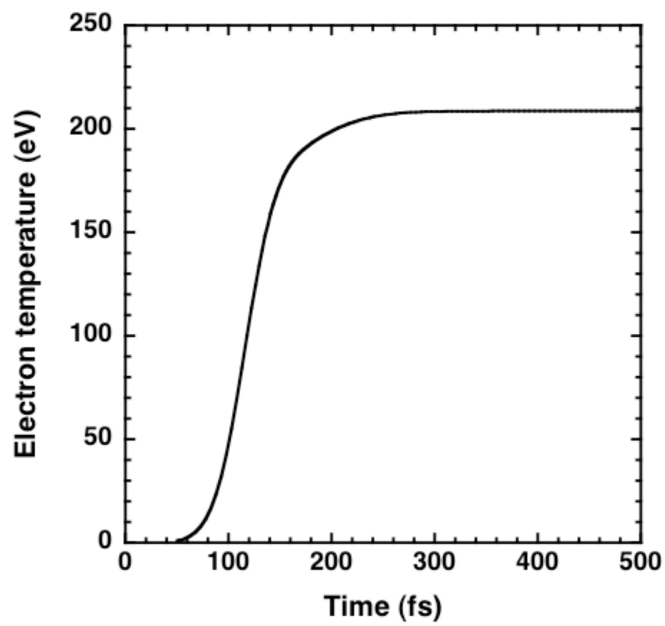

Fig. 3. Electron temperature of Ne plasma versus time.

To model this system we used an ion density of 1018 cm-3 for the Ne gas, which is the same as used in the Saturn pulsed power experiments that were done many years ago [3]. Because of the complexity of the atomic model for near neutral sequences we started the calculation in O-like Ne with an electron temperature of 1 eV and an ion temperature of 0.025 eV. In He-like Ne the atomic model had 252 levels including doubly excited states up to 2p5f while O-like Ne has 1537 levels. The CRETIN code [6] was used to model the kinetics in one dimension (1D). We created an input file that represented the monochromatic X-FEL beam at 1127 eV with a full width of 1.1 eV and a 100 ps full-width half maximum (FWHM) duration Gaussian pulse. The pulse peaks at 200 ps in the various figures. Under these conditions the peak photo-ionization rate for the Ne plasma in the Li-like sequence is 5 psec-1. Figure 2 shows the ionization fraction of the various iso-electronic sequences versus time. One observes that the plasma quickly reaches 40% He-like and 55% Li-like shortly after the peak of the pulse. Figure 3 shows the electron temperature of the Ne plasmas versus time. The plasma quickly reaches an electron temperature of 208 eV while the ion temperature stays near room temperature and only slowly doubles to 0.05 eV by 1100 ps. For these short pulse driven low-density plasmas the ions stay very cold and are decoupled from the electrons.

Another important issue to understand is the fractional populations divided by the statistical weight of the upper laser states and the ground state in He-like Ne. The lower laser states have very small populations initially. Figure 4 shows the fractional populations versus time for the He-like ground state and three of the upper laser levels. One can observe how the 1s and 4p levels are locked together by the strong X-FEL and then diverge as the X-FEL turns off. As the population of the 4p level decays one observes the populations of the 4d and 4f levels rise as collision processes try to equilibrate the populations of these levels. The calculation is done so that the X-FEL pulse peaks at 200 fsec on the time axis. Figure 5 shows the predicted gain for the three strongest laser lines in He-like Ne. The dominant line is the 4f – 3d transition that has a peak gain of 438 cm^{-1} at 1067 fs. This line has a FWHM gain duration of 1840 fs. In contrast the 4d – 3p line has a peak gain of 270 cm^{-1} at 496 fs and the 4p – 3s line has a peak gain of 333 cm^{-1} at 301 fs. The 4f – 3d gain peaks almost 900 fs after the peak of the X-FEL drive pulse because of the time needed for electron collisions to transfer population from the 4p level via the 4d level. With these high gains a plasma length of 0.1 cm should be more than sufficient to obtain saturated output for the laser lines. If we look at the absorption coefficient for the 1s – 4p He-like line that is being pumped it has a value of 0.24 cm^{-1} at 200 fs, the peak of the X-FEL pump pulse and remains less than 1 cm^{-1} until 300 fs, which is when the X-FEL pump is mostly over.

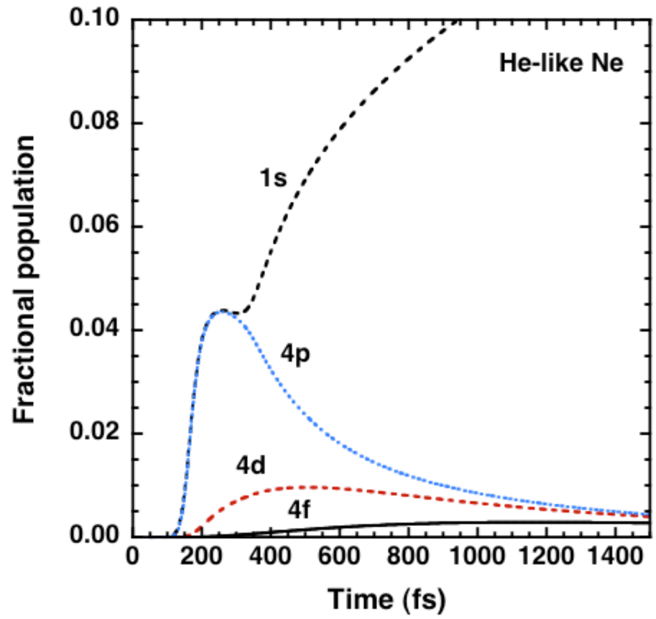

Fig. 4. Fractional population of He-like Ne ground state and upper laser state levels versus time.

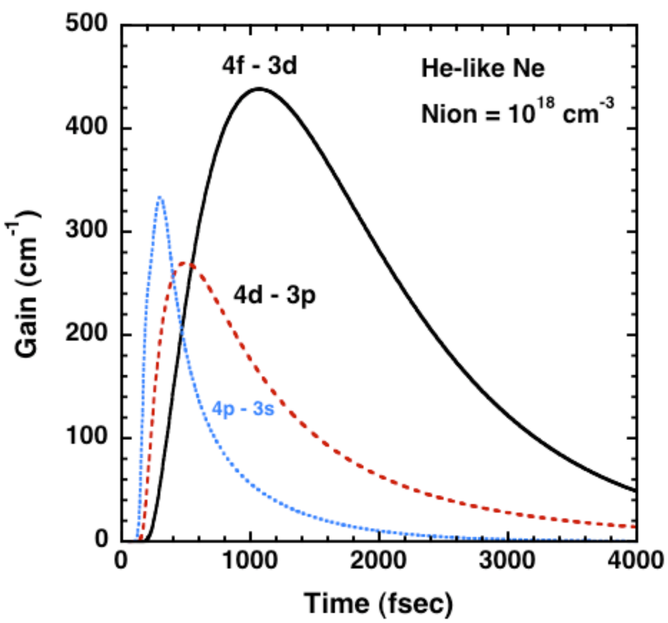

Fig. 5. Gain of three n=4 – n=3 laser transitions of He-like Ne versus time.

4 Conclusions

Since the early days of laser research H-like and He-like resonantly photo-pumped laser schemes have been proposed for producing X-ray lasers. However, demonstrating these schemes in the laboratory has proved to be elusive. One challenge has been the difficulty of finding an adequate resonance between a strong pump line and a line in the laser plasma that drives the laser transition. Given a good resonance, a second challenge has been to create both the pump and laser plasma in close proximity so as to allow the pump line to transfer its energy to the laser material. With the advent of the X-FEL at LCLS we now have a tunable X-ray laser source that can be used to replace the pump line in previously proposed laser schemes and allow researchers to study the physics and feasibility of photo-pumped laser schemes. In this paper we model the Na-pumped Ne X-ray laser scheme that was proposed and studied many years ago by replacing the Na He-α pump line at 1127 eV with the X-FEL at LCLS. We predict gain on the 4f – 3d transition at 231 Å. Given the tunable nature of the X-FEL we are no longer restricted to studying photo-pumping in just the materials that have accidental resonances with strong pump lines but we can now study any ion of interest that falls within the spectral range of the X-FEL. In addition to looking for gain and lasing the X-FEL can also be used to study the kinetics of these laser systems by observing the dynamic evolution of the fluorescent lines.

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